NEW TOOLS FOR ROOF SUPPORT EVALUATION AND DESIGN

Steve Signer and Carl Sunderman
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA USA

ABSTRACT

Researchers at the National Institute for Occupational Safety and Health (NIOSH) have developed several new tools for evaluating roof support performance. A miniature data acquisition system (MIDAS) was developed that can collect readings from up to 16 strain gauges at regular time intervals and store the readings for later retrieval. Three LED lights change from green to yellow, then red, based on the reading levels and/or rates of change of rock movement. This feature can be used to warn miners of rock instabilities. The system can be used with any strain-gauged support (resin bolt, friction bolt, cable bolt) or with a newly developed rock strain strip (ROSS) developed by NIOSH to measure rock strain. A ROSS is grouted in a hole drilled adjacent to the rock support to be evaluated; the deformed shape of the ROSS provides anchorage on either side of the strain gauges. Data from both laboratory tests and field evaluations are presented that describe the capabilities of both the MIDAS and ROSS instruments.

BACKGROUND

Statistics from the Mine Safety and Health Administration (MSHA) indicate that falls of roof remain one of the major hazards in underground mines. From 1997 to 2001, 26 percent of all underground injuries were caused by roof falls. Bauer and Dolinar (2000) indicate that between 1995 and 1998, 98% of roof fall injuries in underground coal mines were caused by sloughing or spalling of opening surfaces (the "skin"), and 77% of roof fall fatalities were caused by massive roof failures.

Many factors cause these failures. Skin failure can be due to weathering or it can be caused by roof bending, compression failure, tensile stresses, shear, etc. Massive failures are generally caused by roof bolt failure or loss of roof bolt anchorage. The anchorage capacity of roof bolts can be significantly lower in weaker rock, which leads to bolt pull-out failures and may be a significant factor in massive roof falls in weak ground.

Researchers have worked for many years to develop theories and design methods for the selection of roof supports. An excellent review is given by Choquet and Hadjigeorgiou (1993). Studies have shown that bolt loading is often much higher than the predicted designs. Field measurements of 92 instrumented bolts at eight coal mines indicated that 75% of the bolts reached the yield point of the steel, and 50% exceeded the yield point (Signer 2000). These values were two to three times the design prediction of dead weight loading. This shows that application of design methods must be combined with field measurements to ensure proper support selection.

Although studies conducted by researchers from the former U.S. Bureau of Mines and NIOSH have demonstrated that geotechnical instruments can be used effectively to identify and monitor ground control hazards, modern rock mechanics instruments are rarely used by the mining industry in the United States. Data are collected by either taking readings with hand-held instruments or installing electronic data acquisition systems. Hand readings are very labor intensive and tend to be collected infrequently. Typical continuous electronic data acquisition systems are large, difficult to use, and expensive. Many mines, especially smaller operations, do not have the expertise or resources available to design an effective instrumentation plan, properly install and monitor a variety of instruments, and analyze and interpret the electronic readings obtained from the instruments.

NIOSH developed a miniature data acquisition system (MIDAS) that addresses these problems. This system has the potential to make the use of geotechnical instruments in underground mines more feasible. Another instrument developed by NIOSH is a "rock strain strip" (ROSS) that, in conjunction with MIDAS, can measure rock movement more accurately. The purpose of this paper is to provide an overview of this new instrument, its capabilities, and its use in improving evaluations of roof support.

INSTRUMENTS

Miniature Data Acquisition System (MIDAS)

MIDAS (figure 1) is designed to collect strain measurements from resistive sensors, such as strain-gauged bolts, cable bolts, ROSS's, and string pots. MIDAS is attached directly to a ROSS so no long lead wires are required. Up to 16 monitoring channels can be selected. A 125-kbyte, on-board flash memory can store 2,192 data scans if all 16 channels are read. An on-board clock is used to set the scan rate for readings in real time, and time-stamps each scan. A thermistor records temperature with each data scan, and a RS232/RS485 port

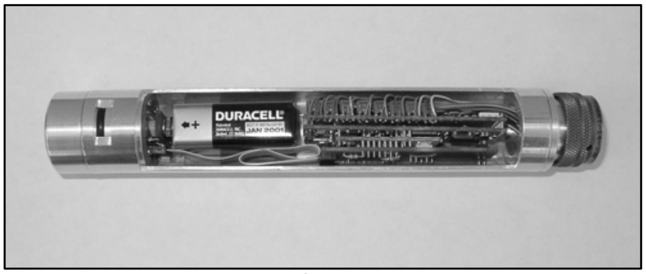

Figure 1.–MIDAS demonstration model

Figure 2.–MIDAS LED lights and serial connector

can communicate with any computer. MIDAS has an experimental MSHA approval rating for use in return air.

The MIDAS has an amplifier gain and frequency response that can be adjusted for the requirements of various instruments. The gain has seven settings that vary the measurement range from ±35 mV to ±2.25 V. Using strain gauges with a gauge factor of 2, the gain setting used for large strain tests has a measurement range of ±562.5 mV (250,000 microstrain), which has a resolution of approximately 0.067 mV (0.03 microstrain). A computer program was written to set up MIDAS, plot data, convert the information to engineering units, and write to a spreadsheet. This software makes MIDAS set-up and data processing easier.

The low power requirement enables long-term testing. A 9-V battery will provide enough power to take daily readings on 16 channels and power the light-emitting diode (LED) lights for 6 months. If the battery voltage does run low, the data are still available for downloading. The small size (17 mm wide by 74 mm long by 17 mm high [0.67 by 2.90 by 0.67 in]) makes the MIDAS adaptable for use in almost any location. Because the MIDAS is so small and self contained, it can monitor instruments while a continuous miner is cutting coal.

Strain is measured by the MIDAS's datalogger, stored in memory for later retrieval, and activates the LED lights (figure 2). These lights change from green to yellow to red to warn miners of hazardous conditions. The threshold levels to change the LED colors can be set by the end user to adjust for different types of ground conditions and instruments.

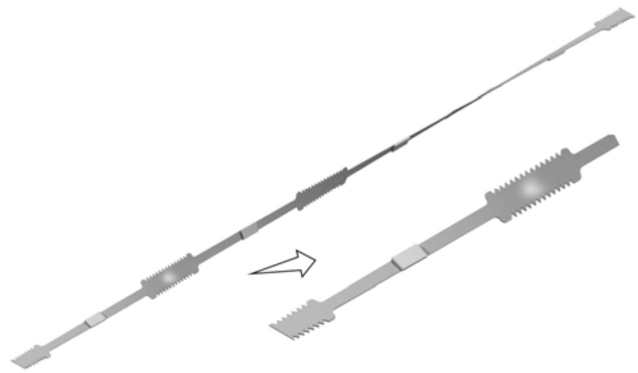

Figure 3.–Rock strain strip

Rock Strain Strip (ROSS)

The ROSS (figure 3) is made of thin (1.5-mm [0.060-in]) stainless-steel plate that has been cut and twisted at every foot along the ROSS's length. Type 304 stainless steel was selected for the ROSS because it has high ductility (70%). (The ductility of typical steel bolts used for roof support is between 6% and 16%.) This means that the ROSS will not break prior to tensile failure in typical roof supports. This type of stainless steel is also corrosion resistant, which helps to preserve the instrument in long-term tests.

The shape of the ROSS is critical. This shape is similar to that of a dog bone between two adjacent sets of teeth. At each set of teeth, the ROSS is twisted 60°, which allows the ROSS to be installed in a hole that has not been drilled perfectly straight. The twist also centers the ROSS in the hole. This shape causes the ROSS to stretch at the thinnest points, which is also where the strain gauges are positioned. The size and number of teeth are important to anchoring the ROSS into the grout when the ROSS is placed in the hole. The tooth area in contact with the grout must balance the force-deflection relationship of both the grout and the stainless steel.

High-elongation strain gauges rated for 20% strain are also attached every foot along the length of the ROSS, but between the twists. The surface is sand blasted so that the gauges will remain attached at high strain levels. The glue is rated for both high elongation and minimal amounts of long-term creep. Two sealants are applied to the strain gauges to protect them against oxidation. After the lead wires are applied, electrical tape is used to keep the lead wires from becoming embedded in the grout after installation. The ROSS is attached to a pipe with a T where the wires from the strain gauges attach to an electrical connector, as shown in figure 4.

The ROSS was designed to be installed in a 38-mm (1.5-in) diam hole. Just prior to installation, a small (6 mm outer diameter) air vent is attached to the ROSS and run along the length of the instrument. The ROSS is placed in the hole, and the edges of the plastic pipe are sealed against the hole wall with two-part, fast-setting epoxy. A flexible hose is attached to the threaded connection, and grout is pumped to fill the hole and encase the instrument in the mine roof.

After the fast-setting grout hardens, the teeth cut into the metal ROSS keep the instrument anchored when the rock begins to move. The strength of the grout must be sufficient to develop the ultimate strength of the ROSS. It should be slightly expansive to avoid shrinkage cracks, able to maintain its strength if it is submersed in water, easy to apply, and inexpensive. The grout selected was

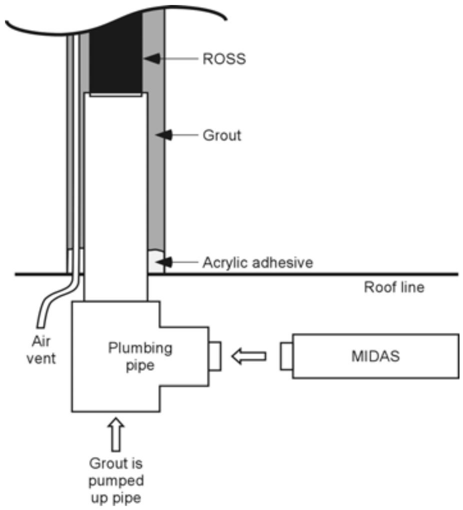

Figure 4.—End connection on ROSS

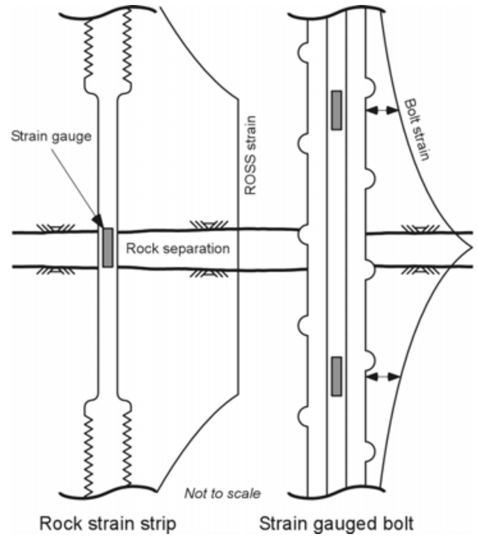

Figure 5.—Strain behavior of ROSS and instrumented bolt

Thorogrip.[1] It is a portland cement-based material with a water-to-grout ratio of 0.17 and can be easily pumped. It sets in 15 minutes, is slightly expansive, and achieves an unconfined compressive strength over 2,000 psi in 1 hour.

The gauges measure strain in the steel caused as the rock moves between the two adjacent sets of teeth. The size of the ROSS and the number of sets of teeth can be adjusted for different types of applications and must be correctly engineered on the basis of the strength of the grout and the strength of the rock. Thermal expansion is 17 microstrain per degree Celsius, which is close to the thermal expansion of readily available commercial strain gauges. Yield strength is 215 MPa (31,200 psi), and ultimate tensile strength is 505 MPa (73,200 psi). The instrument can measure up to 170,000 microstrain of rock movement.

SUPPORT EVALUATIONS

The ROSS measures strain (rock movement) in a different manner than do instrumented rock bolts (figure 5). The cross-sectional area of a twist section is twice as large as the area where a strain gauge is positioned. So, when the rock moves, that movement is distributed over the length between the twists.

The definition of strain is—

$$\varepsilon = \Delta L / L$$

where ε = strain,
ΔL = change in length
and L = gauge length.

ΔL equals rock movement in the roof. The gauge length for the ROSS used in these tests is approximately 200 mm (8 in). Rock movement is then equal to instrument strain times gauge length (figure 6). This calculation ignores the small amount of friction between the side of the ROSS and the grout and the strain relaxation in the ROSS caused by elastic deformation of the grout at the contact point of the teeth.

[1] Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

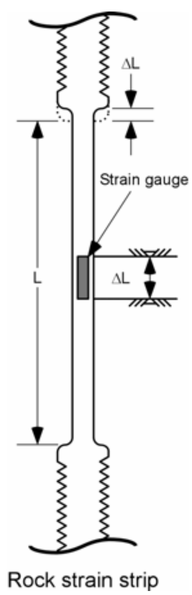

Figure 6.—Strain on ROSS

The advantage of using a ROSS to measure rock movement is that the ROSS can measure 1 microstrain without significant anchor slippage. The accuracy of other instruments varies from 0.025 to 1 mm (0.001 to 0.04 in). If anchor spacings are 300 mm (1 ft) apart, then strain over these lengths would range from 83 to 3,300 microstrain. These figures do not include measurements of anchor slippage. Thus, many types of rock monitoring instruments are totally ineffective for monitoring strain changes in typical roof supports.

Figure 5 shows the strain distribution along the length of a grouted bolt in response to rock movement. Strain is transferred to the bolt via mechanical interlock at the interfaces between the resin grout and the rock and the resin grout and the bolt. The rock movement causes shear in the grout and at both the resin-rock and resin-bolt interfaces. After the peak shear strength at these interfaces is reached, additional movement or slip takes place that transfers the strain farther from the point of the initial rock movement. Resin grout shrinks slightly after it hardens, which creates small voids that allow the steel bar to slip before it becomes locked in the hole. These slippages result in lower strain levels in a grouted bolt than would be generated in a ROSS. An excellent study by Aziz et al. (2000) showed the effects of bolt and rib deformation on shear stress at the bolt-grout interface. Peak shear in their test samples was reached with 5 mm (0.2 in) of movement, after which peak shear decayed to residual shear.

Figure 5 shows the difference in how a grouted bolt and a ROSS respond to rock movement. Laboratory tests showed that the ROSS captures 98% of the rock movement between one set of teeth, whereas the grouted bolt dissipates rock movement over a much longer length. Previous studies (Serbousek and Signer 1987; Littlejohn 1993) have shown that the bolt anchorage length can range from 0.3 to 1 m (1 to 3.3 ft). Thus, if only one rock separation occurred in a mine roof, the ROSS would show the effect at only one gauge position, whereas the instrumented bolt would show effects at several positions. This suggests that the ROSS would better define rock movement at a specific location. Furthermore, with an instrumented bolt, it is not possible to tell if bolt anchor slippage occurs because the strain level drops to zero at the end of the bolt farthest from the roof. Installing a ROSS next to an instrumented bolt would allow researchers to determine if anchor slippage has actually occurred.

TEST RESULTS

Figures 7 and 8 compare the behavior of a ROSS and a No. 7, grade 60, strain-gauged rebar bolt installed with slow-setting resin in a mine where the immediate roof consisted of carbonaceous shale and mudstone rock interbedded with coal layers. Note that the y-axis scale of figure 7 varies. Both instruments were 2.4 m (8 ft) long and were installed within 250 mm (10 in) of each other at the edge of a cross-cut in an intersection before the cross-cut was extended into the intersection. The instrumented bolt had five pairs of strain gauges positioned at equal distances apart along its length, and the ROSS had eight pairs of equally spaced gauges.

The initial strain increase shown in figure 7 resulted from roof movement as the cut was made. Readings were then taken continuously for the next 7 weeks. The greatest amount of movement on the ROSS occurred at the midpoint and is shown in figure 7*C*. The strain level of the ROSS was approximately four times greater than the strain level in the instrumented bolt. The strain measurement of 8,000 microstrain converts to approximately 1.6 mm (0.064 in) of movement. This amount of rock movement produced strain in the bolt that was transferred along the length of the bolt. After the initial movement, however, the strain in the bolt stopped increasing.

Both the first position on the bolt (at 406 mm) and the ROSS (at 305 mm) (figure 7*A*) indicate low initial strain increases of 100 microstrain for the bolt and -300 microstrain for the ROSS. As the continuous miner cut through the entry, it pressed up on the vent tube, which pushed up on the ROSS (but not on the adjacent instrumented bolt) and caused the initial position on the ROSS to show negative strain. The rate of increase after this initial movement showed that the rate of change for these two gauges was similar. The strain level at the second position (figure 7*B*) on the instrumented bolt compared closely with that on the ROSS. On the bolt, the strain level was likely to have been affected by the much-larger amount of rock movement at the third position (figure 7*C*). The amount of increase in strain after the initial movement was higher for the bolt than for the ROSS and was most likely caused by strain redistribution from the third position. A similar ratio of strain on the ROSS to strain on the bolt during initial rock movement is seen between positions 3 (figure 7*C*) and 4 (figure 7*D*), but was much larger at position 5 (figure 7*E*). The rate of

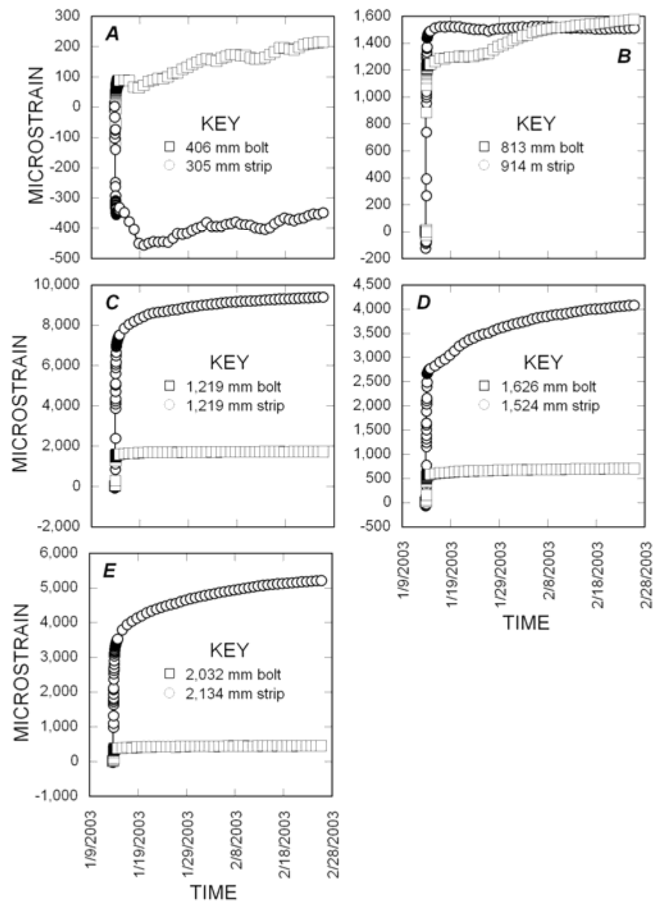

Figure 7.–Comparisons of strain over time on instrumented bolt and ROSS at five positions.

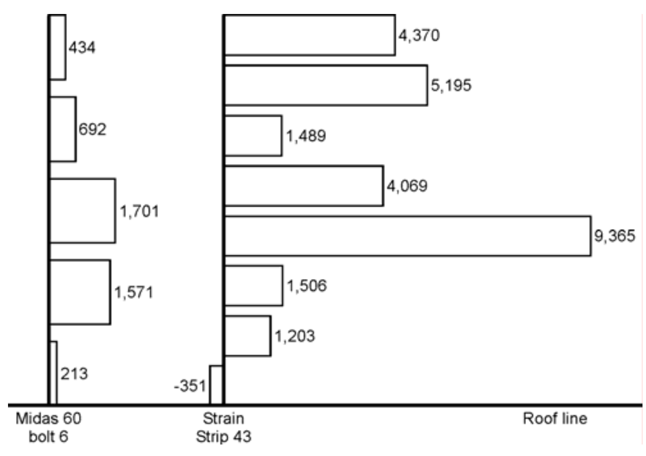

Figure 8.—–Comparison of strain on instrumented bolt and ROSS

increase in strain after initial movement follows the same pattern, with the largest increase at position 5. Table 1 shows the ratio of ROSS strain to bolt strain for the five strain gauge positions at three different times.

Table 1.—Ratio of strain on ROSS to strain on instrumented bolt

Date, time	Strain gauge position				
	A	*B*	*C*	*D*	*E*
1/14/03, 0:00	-5.73	1.16	4.46	4.74	8.53
1/14/03, 15:41	-3.88	0.83	4.80	4.81	9.68
2/25/03, 15:16	-1.65	0.77	5.51	5.88	11.98

The ratio of strain shown in table 1 indicates a decrease with time at positions *A* and *B*, a steady level with time at positions *C* and *D*, and a significant increase with time at position *E*. The ratio values indicate a similar pattern where position *A* and *B* are low, position *C* and *D* are medium, and position *E* is high. The negative value of position *A* was caused by mining equipment pushing up on the instruments.

Most of the rock movement occurred at 1.2 m (4 ft) from the roof line and caused the roof bolt to load at the 0.8- and 1.2-m (2.6- and 4-ft) positions. Significant amounts of rock movement occurred at the 2.1- and 2.4-m (7- and 8-ft) positions on the ROSS (figure 8) that were not recorded on the instrumented bolt. The ratio of strain on the ROSS to strain on the instrumented bolt indicates the effectiveness of the grout in providing anchorage for the bolt.

SUMMARY

MIDAS can make the use of geotechnical instruments easier and cheaper and can warn miners of hazardous conditions. When used in combination with the ROSS, the effectiveness of roof supports can be evaluated to a level of detail that has not been possible before. The data show that the ROSS can determine the amount of rock movement very accurately and locate the occurrence within the distance between the teeth. Using both a ROSS and an instrumented bolt can lead to a new understanding of bolt-grout-rock interactions. The results show that strains recorded by the ROSS are higher than strains measured by instrumented bolts. The anchorage capacity of the ROSS is much higher and provides a method for evaluating the anchorage properties of bolts in situ.

Several ongoing tests are being conducted by NIOSH and will enable more comparisons of instrumented supports and ROSS's to be made to study how different types of supports respond to rock movement. Additional research is required to study a number of different variables, including the effects of rock strength, roof bolthole properties, size of grout annulus, and grout strength.

ACKNOWLEDGMENTS

Development of the ROSS was a team effort. Many different approaches and ideas were evaluated. I would especially like to thank Dennis Cox, JoAnne Johnson, Rich Rains, Tom Brady, and Richard Curtin for the ideas and hard work that made this instrument possible.

REFERENCES

Bauer, E.R., and Dolinar, R.J. 2000. Skin Failure of Roof and Rib and Support Techniques in Underground Coal Mines. In *Proceedings: New Technology for Coal Mine Roof Support*, ed. by C. Mark, D. R. Dolinar, R.J. Tuchman, T.M. Barzak, S.P. Signer, and P.F. Wopat. NIOSH Information Circular 9453, pp. 99-110.

Choquet, P., and J. Hadjigeorgiou. 1993. The Design of Support for Underground Excavations. In: *Comprehensive Rock Engineering: Principles, Practice, and Projects*. Pergamon Press, Vol. 4, pp. 313-345.

Signer, S.P. Load Behavior of Grouted Bolts in Sedimentary Rock. 2000. In *Proceedings: New Technology for Coal Mine Roof Support*, ed. by C. Mark, D. R. Dolinar, R.J. Tuchman, T.M. Barzak, S.P. Signer, and P.F. Wopat. NIOSH Information Circular 9453, pp. 73-80

Serbousek, M.O., and S.P. Signer, S.P. 1987. Linear Load Transfer Mechanics of Fully Grouted Bolts. Bureau of Mines Report of Investigations 9135, 17 pp.

Littlejohn, S. 1993. Overview of Rock Anchorages. In: *Comprehensive Rock Engineering: Principles, Practice, and Projects*. Pergamon Press, Vol. 4, pp. 413-450

Aziz, N., B. Indraratna, and Y. Wang. 1999. Study of Shear Loading and Bolt Load Transfer Mechanics under Constant Normal Stiffness Conditions. In: *Proceedings, 18th International Conference on Ground Control in Mining*, ed. by Syd S. Peng (Univ. of WV, Morgantown, WV, Aug. 3-5, 1999), pp. 239-247.

NEW TOOLS FOR ROOF SUPPORT EVALUATION AND DESIGN

Steve Signer and Carl Sunderman
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Spokane, WA USA